

Hyperspectral Remote Sensing of the Coastal Ocean: Adaptive Sampling and Forecasting of In situ Optical Properties

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LONG-TERM GOAL

We are developing an integrated rapid environmental assessment capability that will be used to feed an ocean nowcast/forecast system. The goal is to develop a capacity for predicting the dynamics in inherent optical properties in coastal waters. This is being accomplished by developing an integrated observation system that is being coupled to a data assimilative hydrodynamic bio-optical ecosystem model. The system was used adaptively to calibrate hyperspectral remote sensing sensors in optically complex nearshore coastal waters.

OBJECTIVES

Our objectives were to

- 1) develop and deploy moored, shipboard, and autonomous bio-optical systems in the coastal ocean to ground-truth remote sensing imagery,
- 2) use rapid environmental assessment techniques to quantify the physical, chemical and biological processes that define the spatial and temporal variability in the spectral IOPs for the nearshore coastal ocean during summer-time upwelling,

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14. ABSTRACT We are developing an integrated rapid environmental assessment capability that will be used to feed an ocean nowcast/forecast system. The goal is to develop a capacity for predicting the dynamics in inherent optical properties in coastal waters. This is being accomplished by developing an integrated observation system that is being coupled to a data assimilative hydrodynamic bio-optical ecosystem model. The system was used adaptively to calibrate hyperspectral remote sensing sensors in optically complex nearshore coastal waters.					
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3) refine and calibrate existing hyperspectral optical models to derive IOPs from remotely sensed data using the above datasets and,

4) in collaboration with other principal investigators couple a radiative transfer ecosystem module to the data-assimilative hydrodynamic model.

Our analysis efforts focused on inverting signatures to bulk *in situ* constituents, use the derived phytoplankton signatures as inputs to bio-optical productivity models, define how the inherent optical properties impact both operational horizons of emergent light fluxes and remote sensing reflectance measured by the international constellation of satellites and aircraft. Finally we are conducting hindcast studies with the coupled optical/physical numerical model.

APPROACH

We conducted a series of Coastal Predictive Skill Experiments (CPSE) at the Long-term Ecosystem Observatory (LEO-15) in order to understand the physical forcing of the nearshore optical properties. HyCODE, in conjunction with the ONR sponsored Coastal Ocean Modeling and Observation Program (COMOP), anchored the CPSE experiments. The physical results from these efforts are highlighted in the COMOP progress report. To this end, coordinated shipboard (physical and bio-optical) and AUV adaptive sampling surveys of the upwelling centers were conducted based on the real-time remote observations and model forecasts. The observational capability was used then to characterize and model the variability in the physics and the associated in-water optical properties. The goal was to ground-truth hyperspectral imagery collected by COIS sensors mounted on aircraft. Data synthesis efforts in the last year have focused on getting out a series of peer-reviewed papers combined putting together a special issue of JGR focused on the CPSEs.

WORK COMPLETED

The field-work was accomplished at LEO and focused on using the dynamical forecasts generated through the Regional Ocean Model (ROMs) to organize the field assets of the HyCODE program. These forecasts, real-time CODAR fields, and *in situ* data from the autonomous nodes assisted in choosing flight missions for the aircraft (PHILLs 1, PHILLs 2, AVIRIS, Proteus, SPECTIR) and position three ships under the aircraft for *in situ* validation. Furthermore *in situ* profiling nodes were outfitted to measure a full suite of inherent optical properties. Field sampling was coordinated through the modeling/observation system and allowed for 1) 16 clean overflights providing hyperspectral ocean color data with complete remote sensing ground truth data from the research fleet, 2) 5 days with more than two aircraft flying at one time allowing for one of the first times vicarious calibration between aircraft systems, and 3) calibration of atmospheric parameters using NASA-funded aircraft. During the three years of field work in excess 400 discrete samples were collected and have been analyzed in the lab for filter pad absorption spectra, particle size, phytoplankton pigmentation, and organic carbon/nitrogen content.

The ROMs systems was coupled to the EcoSim model. This required substantial modification of the EcoSim model, which was not written in to run in parallel. ROMS is a free-surface, hydrostatic, primitive equation model initially based on the s-coordinate Rutgers University Model (SCRUM). ROMS was rewritten by the UCLA and Rutgers ocean modeling groups to improve its numerics and efficiency in single and multi-threaded computer architectures. New features include high-order advection schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; radiation boundary conditions; and data assimilation. EcoSim, which is upper ocean ecological model, was successfully coupled to the ROMS model and the shared memory parallel version (using OpenMP) of the ROMS/EcoSim code that we

used to produce forecasts on the New Jersey coast for ONR's COMOP/HyCODE program in July 2001 required 25 hours of wall clock time to process a 31 day simulation of a 100 x 240 (horizontal) x 25 (vertical) grid when executing on 16 (out of 256) processors of the NRL Origin3800 supercomputer (neo.cmf.nrl.navy.mil). Additionally, Ecolight, a version of the Hydrolight 4.1 radiative transfer model, was added to the ROMS/EcoSim modeling system. The advantage of adding Ecolight is that it provides an accurate solution of the RTE for any water body, given the absorption and scattering properties of the water body, the incident sky radiance, and the bottom reflectance (for finite-depth waters) but it runs one thousand times faster than the standard version of Hydrolight.

RESULTS

During the experiment we experienced a wide gradient of hydrographic conditions, which provided a wide dynamic range ideal for calibrating the aircraft hyperspectral sensors. The adaptive sampling strategy allowed us to optimize this calibration exercise, with 16 days of high quality *in situ* and aircraft data. Currently personnel FERI, NRL-Stennis, and Rutgers have been comparing the *in situ* and aircraft optical data. The conditions that dominated the optical signals varied between the two years. Summer 2000 was dominated by a plume of Hudson River water. In contrast alternating upwelling and downwelling events dominated summer 2001. Some selected results from this project are highlighted below.

Objective water calibration from space We developed an objective technique using multivariate cluster analysis combined with a newly developed genetic expression algorithm developed as part of *Drosophila* genome program to objectively determine the number of water types in the region based on ocean color and sea surface temperature measurements. Then, through boundary analysis of the water types identified, we were able to map the boundaries of the major water types and to describe the relative differences. HyCODE results suggest this approach can be used to track the development of water masses and is a step forward as the analysis combines the information of multiple parameters to describe water masses. It is an effective tool in detecting water masses not readily recognizable in a single dimension (e.g. just SST or ocean color, Figure 1).

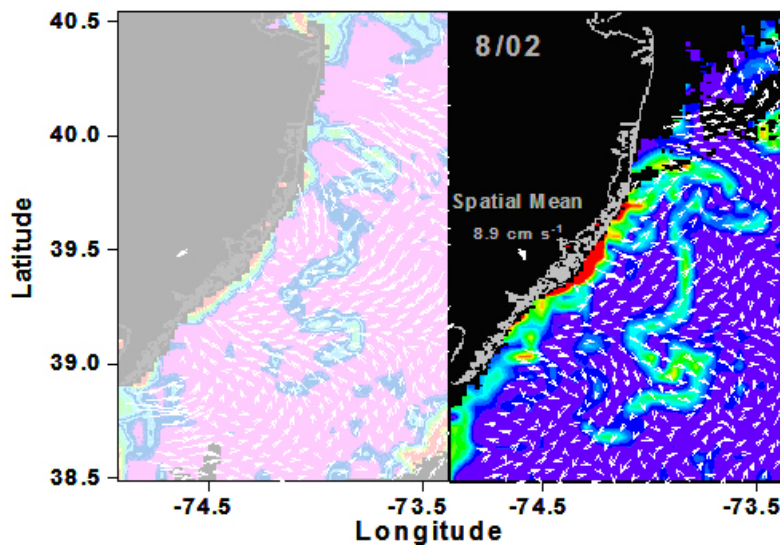


Figure 1: Calculated water mass boundary gradients overlaid with surface current fields with the special mean subtracted. Areas with large gradients are coincident with convergent and divergent areas indicating that local current structure accounts for the gradient locations.

Calibration of IOP algorithms The *in situ* optical measurements were compared to satellite-derived estimates of the inherent optical properties (IOP). At 442 nm, *in situ* absorption values ranged from less than 0.2 to over 1.5 inverse meters. Satellite estimates of backscatter ranged from 0.002 to 0.03 inverse meters at 442nm and showed significant variability in time and space, reflecting the high frequency events associated with wind-mixing, storms and coastal upwelling. Despite this variability, there was good qualitative agreement between the satellite derived IOP estimates and *in situ* IOP measurements. Both absorption and backscatter values increased near-shore, reflecting enhanced concentrations of phytoplankton, sediments and dissolved organic matter.

Inversion of *in situ* data and optical discrimination of water masses: We developed a method that inverts the bulk signal IOPs measured with *in situ* instruments. Good agreement was achieved between measured and modeled particulate and phytoplankton spectra. The inversion method could predict ($p < 0.05$) the concentration of chlorophyll *c* and phycobilin-containing phytoplankton. Water masses could be delineated optically and were combined with temperature and salinity data to extend classical T-S water mass analysis into multi-dimensional space using derived inverted optical parameters. Such approaches show promise for highly dynamic nearshore coastal waters (see Figure 2 for one example).

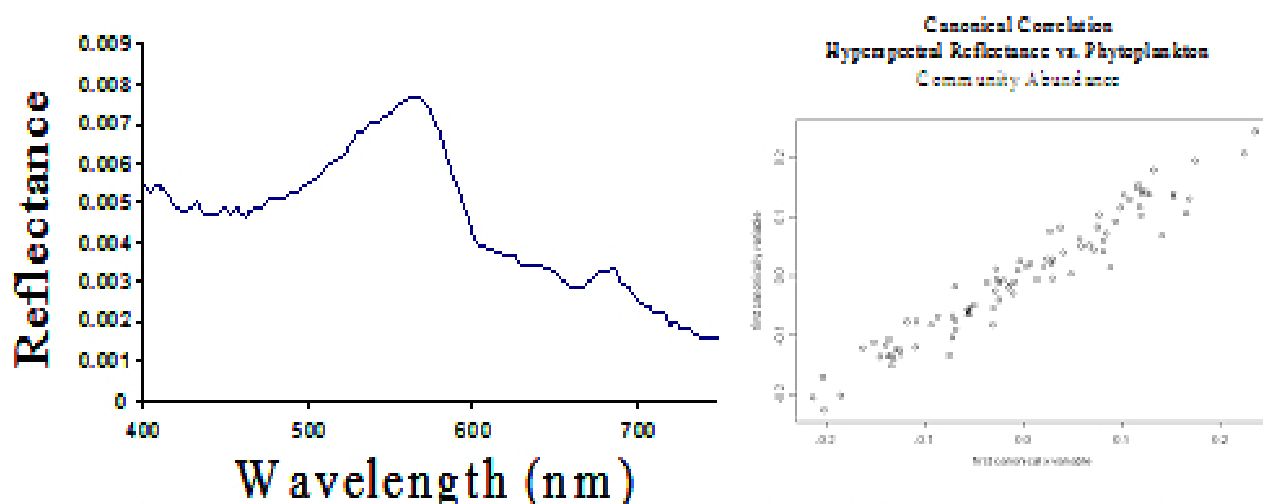


Figure 2: The relationship between temperature, salinity and dissolved organic parameter using the databases collected during HyCODE ($n > 15,000$). The CDOM information on concentration (CDOM *wt*) and composition (CDOM slope) could differentiate the cold pool bottom water from the Mid Atlantic Shelf (redbox) and riverwater (orangebox).

Bio-optical models for primary productivity. Using the inversion method (above) the spectral absorption of phytoplankton was calculated and combined spectral scalar irradiance derived from in-water time series collected with the Leo electro-optic fiber optic cable. The derived estimates of the spectrally-weighted absorption coefficient were used as input to a bio-optical model to compute primary productivity. Modeled integrated water column productivity were within 11% of measured productivity results using ^{14}C incubations.

Phytoplankton community composition prediction from hyperspectral reflectance. The adaptive sampling network was used to relate the impact of the episodic upwelling to the dynamics in bulk phytoplankton biomass and community structure. The dynamics in phytoplankton communities was used to understand the observed variability in hyperspectral remote sensing reflectance. Peak chlorophyll biomass tracked the maximum density gradient, and increasing surface phytoplankton

biomass was associated with decreasing stratification offshore over time. Diatoms dominated the study site, however significant shifts to cyanobacteria and dinoflagellate communities were observed and associated with downwelling. Differences in phytoplankton absorption significantly altered the remote sensing reflectance suggesting mapping algal community structure is possible using above water hyperspectral reflectance measurements (Figure 3).

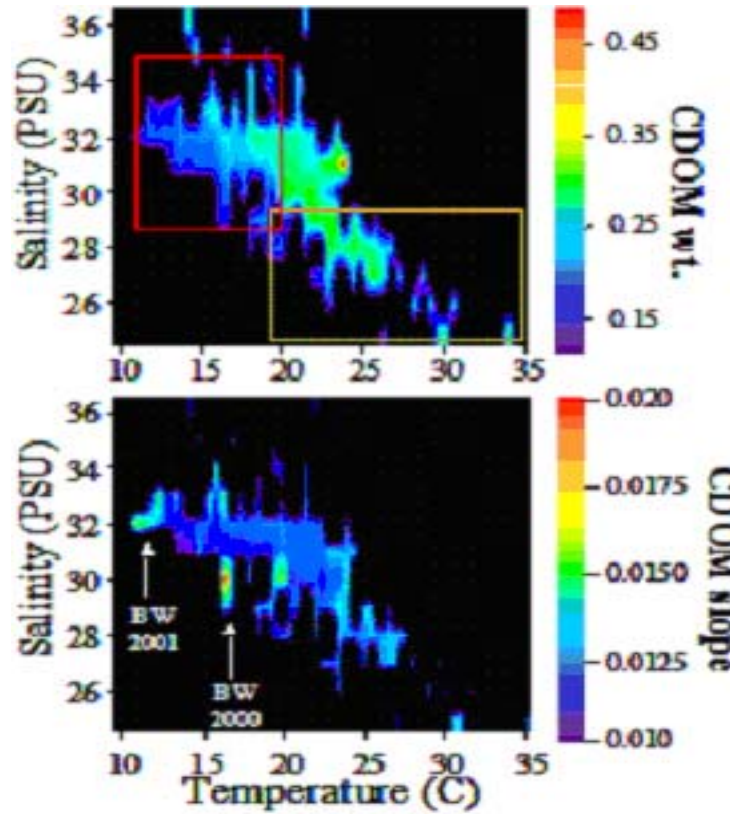


Figure 3: *Measured above water reflectance during HyCODE. Discriminant analysis was used to find the wave lengths most effective at describing the community variability.*

IMPACT/APPLICATIONS

An integrated system for predicting the 3-dimensional structure of coastal currents, water density and in-water optical properties on the time scales of days is essential to numerous naval operations such as mine counter measures, special forces operations, amphibious landings, and shallow water anti-submarine warfare. Hyperspectral ocean color measurements can be to map in-water constituents in areas of high naval interest and the derived algorithms will impact range of applied needs including mine counter measures, diver visibility, and bioluminescence potential. Finally hydrodynamic/optical forecasting system provides the key to integrate and forecast the observed optical properties over time. HyCODE has played a central role to developing optical REMUS AUV and optical Webb Glider. For the Webb Glider it is currently scheduled to take part in the JTFX mine countermeasure efforts in June 2004. All these observation and modeling systems are relocatable and will be key for future naval operations and homeland defense.

TRANSITIONS

The data is being freely shared. Data will be disseminated to the ONR WOOD database. Data that is just being finished processed will be burned to data CD's and is available via one-way FTP. The optical data is currently being utilized by NRL, NSF and NASA remote sensing projects. The ongoing real-time data, for which the HyCODE program was central to its development, continues to be accessed via the web (over 100,000 hits/day) by the general public, Naval METOC groups, NAVO, NOAA Oil Spill response teams, and the U.S. Coast Guard.

RELATED PROJECTS

There were over 27 major institutional partners during the 2000-2001 experiments a large number supported by the HyCODE program. These efforts also complemented other independent efforts such as 1) validation of NAVAIR's KSS Lidar system, 2) ONR-YIP funded AUV bioluminescence prediction efforts, 3) ONR-STTR sponsored efforts to develop a "smart" fleet of automated Webb Gliders, 4) SeaSpace Inc. efforts to intercalibrate the international constellation of ocean color satellites, 5) calibration and refinement of a suite of NRL-derived satellite algorithms, 6) calibration of atmospheric parameters with NASA's atmospheric Chesapeake Lighthouse and Aircraft Measurements for Satellites experiment, 7) field infrastructure for NASA's YIP and PECASE remote sensing projects, and 8) model development for ONR's CBLAST Program.

PUBLICATIONS RESULTING FROM HYCODE SUPPORT

(What HyCODE contributed) (**graduate students or post-doctoral researchers)

Schofield, O., Gryzmiski, J., Bissett, P., Kirkpatrick, G., Millie, D. F., Moline, M. A. Roesler, C. 1999. Optical monitoring and forecasting systems for harmful algal blooms: Possibility or pipedream? *Journal of Phycology*. 35: 125-145. (*HyCODE results used in the manuscript to illustrate inversion approaches*)

Kerkhof, L., Voytek, M., Millie, D. F., Sherrell, R., Schofield, O. 1999. Variability in bacterial community structure during upwelling in the coastal ocean. *Hydrobiologia* 401: 139-148. (*HyCODE paid for pigmentation analysis*)

Millie, D.F., Dionigi, C.P., Schofield, O., Tester, P.A. 1999. The importance of understanding the molecular, cellular, and ecophysiological bases of harmful algal blooms. *Journal of Phycology* 35: 1353-1355. (*HyCODE provided time*)

Kirkpatrick, G., Millie, D. F., Moline, M. A., Schofield, O. 2000. Absorption-based discrimination of phytoplankton species in naturally mixed populations. *Limnology and Oceanography* 42: 467-471. (*HyCODE provided time and travel for field work*)

Bissett, W. P., Schofield, O., Glenn, S., Cullen, J. J., Miller, W., Pluddeman, A., Mobley, C. 2001. Resolving the impacts and feedbacks of ocean optics on upper ocean ecology. *Oceanography* 14: 3-53. (*HyCODE provided results, time, salary*)

Glenn, S. A 2001. Coastal ocean observatory for studying nearshore coastal processes. *Backscatter* 12: 34-37. (*HyCODE provided results, time, salary*)

- Bissett, P., Schofield, O., Mobley, C. Crowley, M. F., Moline, M. A. 2001. Optical remote sensing techniques in biological oceanography. In: Methods in Marine Microbiology. Paul, J. (ed). Academic Press, London. 30: 519-538. (*HyCODE provided results, time, and salary*)
- Evens, T. J., Kirkpatrick, G. J., Millie, D. F., Chapman, D., Schofield, O. 2001. Xanthophyll-cycling and photophysiological regulation of *Gymnodinium breve* in response to fluctuating natural irradiance. *Journal of Plankton Research* 23: 1177-1194. (*HyCODE provided data, travel to field work*)
- Moline, M. A., E. Heine, J. Case, C. Herren and Schofield O. 2001. Spatial and temporal variability of bioluminescence potential in coastal regions. In: (J. F. Case, P. J. Herring, S. H. D. Haddock, L. J. Kricka and P. E. Stanley eds.) Bioluminescence and Chemiluminescence 2000. World Scientific Publishing Company, Singapore, pp. 123-126. (*Based on HyCODE data*)
- **Grzyski, J., Orrico, C., Schofield, O. 2001. Monochromatic ultraviolet light induced damage to photosystem II efficiency and carbon fixation in the marine diatom *Thalassiosira pseudonanna* (3H). *Photosynthesis Research*. 68: 181-192. (*HyCODE provided the equipment and supplies for this project*)**
- Moline, O., Schofield, O., Grzyski, J. 2002. Impact of dynamic light and nutrient environments on phytoplankton communities in the coastal ocean. In: Modeling Dynamic Systems: Dynamic Modeling for Marine Conservation Ecological Understanding. Lindholm, J. and Ruth, M. (eds) Springer Verlag 144-163. (*HyCODE provided results, time, salary*)
- Schofield, O., Bergmann, T., Bissett, W. P., Grassle, F., Haidvogel, D., Kohut, J., Moline, M., Glenn, S. 2002. Linking regional coastal observatories to provide the foundation for a national ocean observation network. *Journal of Oceanic Engineering*. 27(2): 146-154. (*HyCODE provided results, time, salary*)
- **Komada, T., Schofield, O., Reimers, C. 2002. Fluorescence characteristics of organic matter released from coastal sediments during resuspension. *Marine Chemistry*. 79(2): 81-97. (*HyCODE provided the equipment and supplies for this project*)**
- **Grzyski, J., Schofield, O., Falkowski, P. G., Bernhard, J. M. 2002. *Nonionella stella*, a modern analog to the endosymbiotic origin of diatoms: plastid description and function. *Limnology and Oceanography* 47: 1569-1580. (*HyCODE provided the equipment and supplies for this project*)**
- Millie, D. F., Schofield, O., Kirkpatrick, G. J., Johnsen, G., Evens, T. J. 2002. Using absorbance and fluorescence spectra to discriminate microalgae. *European Journal of Phycology*. 37:313-322. (*Based on HyCODE data*)
- Chang G. C., Dickey T. D., Schofield O., Weidemann A. D., Boss, E., Moline, M. A., Glenn. S. M. 2002. Nearshore physical forcing of bio-optical parameters in the New York Bight. *Journal of Geophysical Research* 10.1029/2001JC001018. (*Based on HyCODE data*)
- **Blackwell, S.M., Case, J., Glenn, S., Kohut, J., Moline, M., Purcell, M., Schofield, O. and C VonAlt. VA 2002. New AUV Platform for Studying Near Shore Bioluminescence Structure In: Stanley, P. E. and Kricka, L. J. editors. Bioluminescence & Chemiluminescence Progress and Current Applications. Singapore: World Scientific. p 197-200. (*Based on HyCODE data*)**

Schofield, O., Bissett, W. P., Frazer, T. K., Iglesias-Rodriguez, D., Moline, M. A., Glenn, S. 2003. Development of regional coastal ocean observatories and the potential benefits to marine sanctuaries. *Marine Technology Society* 37: 54-67. *(Based on HyCODE data)*

Kirkpatrick, G. J., Orrico, C., Oliver, M. J., Moline, M. A., Schofield, O. 2003. Continuous real-time determination of hyperspectral absorption of colored dissolved organic matter. *Applied Optics* 42: 1-5. *(Based on HyCODE data)*

Johnson, D. M., Miller, J., Schofield, O. 2003. Dynamics and optics of the Hudson River outflow plume. *Journal of Geophysical Research*. 10.1029/2002JC001485. 1-9.

Moline, M.A., Arnone, R., Bergmann, T., Glenn, S., Oliver, M., Orrico, C., Schofield, O., Tozzi, S. Variability in spectral backscatter estimated from satellites and its relation to in situ measurements in optically complex coastal waters. *Journal of International Remote Sensing*. (In Press) *(Based on HyCODE data)*

**Tozzi, S., Schofield, O., Bergmann, T., Moline, M. A., Arnone, R. Variability in measured and modeled remote sensing reflectance for coastal waters at LEO-15. *Journal of International Remote Sensing*. (In Press) *(Based on HyCODE data)*

**Oliver, M. W., Schofield, O., Bergmann, T., Glenn S. M., Moline, M. A., Orrico, C. *In-situ* optically derived phytoplankton absorption properties in coastal waters and its utility for estimating primary productivity rates. : *Journal of Geophysical Research* (In press). *(Based on HyCODE data)*

Schofield, O., Chant, R., Kohut, J. T., Glenn, S. M. The evolution of a nearshore coastal observatory and the establishment of the New Jersey Shelf Observing System. *Sea Technology* (In Press). *(Based on HyCODE data)*

Moline, M. A., Blackwell, S., Chant, R., Oliver, M. J., Bergmann, T., Glenn, S., Schofield, O. Episodic physical forcing and the structure of phytoplankton communities in the coastal waters of New Jersey. *Journal of Geophysical Research* (In Revision). *(Based on HyCODE data)*

**Oliver, M. J., Kohut, J. T., Irwin, A. J., Glenn, S. M., Schofield, O., Moline, M. A., Bissett, W. P. Bioinformatic approaches for objective detection of water masses. *Journal of Geophysical Research* (In Revision). *(Based on HyCODE data)*

Schofield, O., Bergmann, T., Bissett, W. P. Moline, M. A., Orrico, C., Oliver, M. Inverting inherent optical signatures in the nearshore coastal waters at the Long Term Ecosystem Observatory: *Journal of Geophysical Research* (In Revision). *(Based on HyCODE data)*

Glenn, S. M., Schofield, O., Bergmann, T., Chant, R., Crowley, M., Cullen, J., Haidvogel, D., Kohut, J., Moline, M. A. Studying the Biogeochemical Impact of Summertime Upwelling Using a Coastal Ocean Observatory. *Journal of Geophysical Research* (submitted). *(Based on HyCODE data)*